AlSb/InAs HEMTs and their Integration with RITDs

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Low-Voltage, High-Speed AlSb/InAs HEMTs

- **Objective:**
  - Develop advanced InAs HEMT technology which will lead to lower noise figure, higher gain, and lower power consumption in microwave/mm-wave receivers and high-speed logic circuits.
- **Technical Approach:**
  - Resolve fundamental material and design issues which are unique to the AlSb/InAs material system.
  - Develop design and fabrication methods to fully realize the performance potential of the system.

Personnel

• **MBE growth**	Brian Bennett, Ben Shanabrook, Allan Bracker, Ming J. Yang
• **MBE characterization**	Brian Bennett, Ming J. Yang, Rich Magno, Allan Bracker
• **E-beam lithography**	Doe Park, Bob Bass
• **HEMT fabrication**	Brad Boos, Doe Park, Wontae Chang
• **HEMT measurements**	Brad Boos, Walter Kruppa, Rich Magno, Wontae Chang Jeff Mittereder, and N. H. Turner
• **Wafer bonding**	Karl Hobart, Fritz Kub
• **RTD/HEMT integration**	Brad Boos, Rich Magno, Mario Ancona
• **Simulation**	Mario Ancona, Walter Kruppa, Ming J. Yang, Brad Boos, Eric Justh

Outline

- Background
- InAsSb channel HEMTs
- TiW/Au gate HEMTs
- 1/f noise characterization
- RITD/HEMT integration
- GaSb transferred substrates
- Summary

Potential Applications

High-speed, low-power consumption electronics needed for light-weight power supplies, extension of battery lifetimes, and high data rate transmission.

- **Low-noise receivers**
  - space-based sensing and communications
  - portable communications
  - micro-air-vehicles (MAVs)
- **High-speed logic circuits**
  - communications, data transmission
  - potential for lowest power-delay product
  - integration with Sb-based RTDs for enhanced functionality and low-voltage operation

AlSb/InAs HEMT Motivation

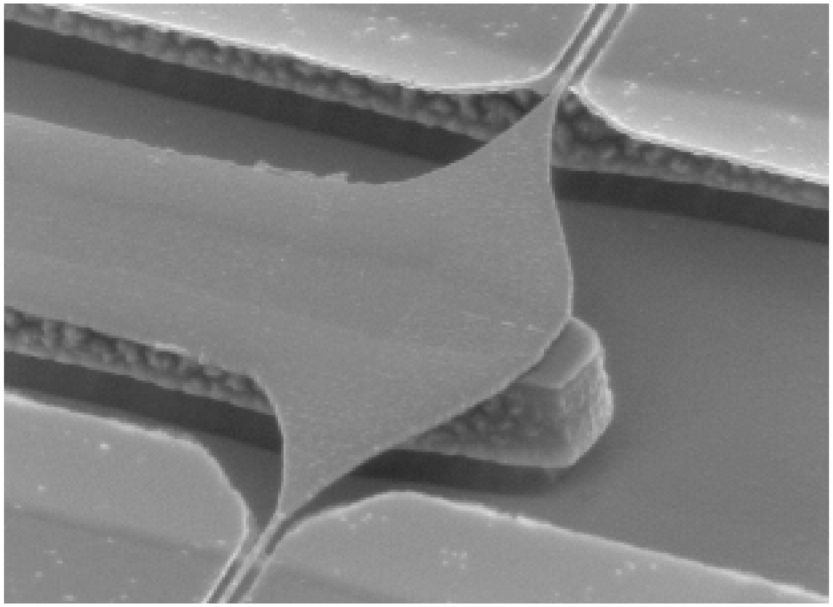
- **Attractive Material Properties**
  - High electron mobility
  - High electron velocity
  - Large conduction-band offset
  - High 2-DEG sheet-charge density

  Potential for High Speed and Low Noise at Low Drain Voltage

- **Design Issues**
  - Impact ionization/High output conductance
  - High gate leakage current

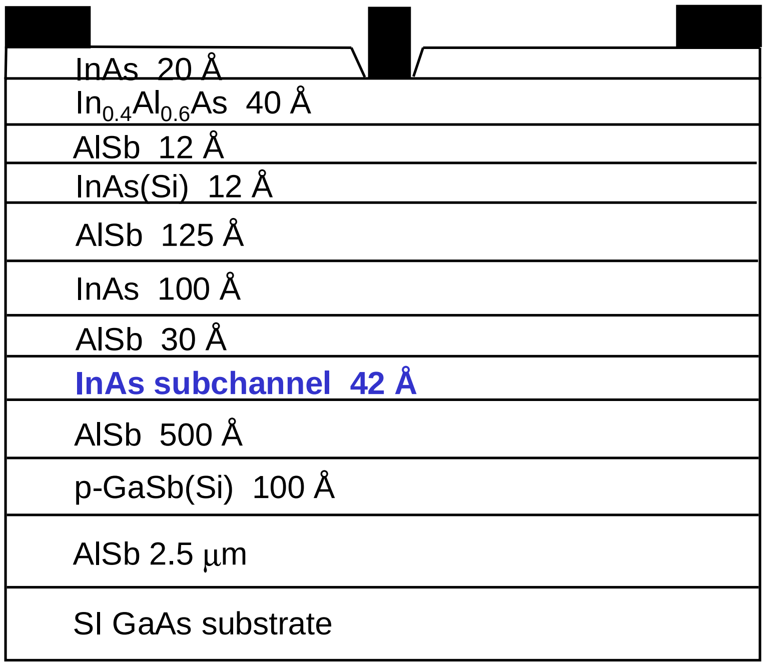
AlSb/InAs HEMT Fabrication

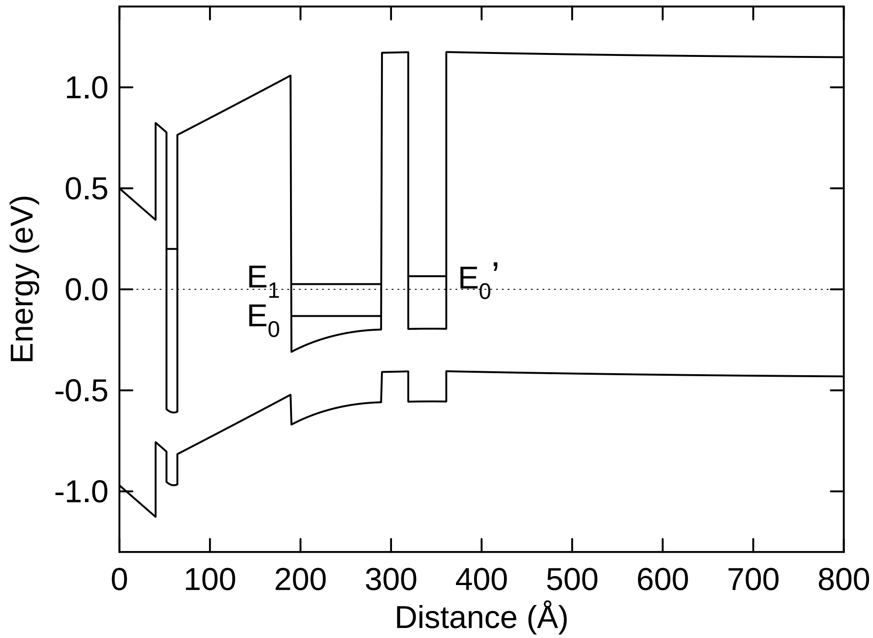
- **Pd/Pt/Au ohmic contacts**
  - Heat-treated at 175°C for 3 hours
  - Pt diffusion barrier
- **InAlAs/AlSb composite barrier**
  - Enables gate recess etch
  - Reduces gate leakage current
  - Reduces kink effect
- **TiW/Au (175Å/1000Å) gate**
  - E-beam lithography
  - Citric acid-based surface treatment
- **Mesa isolation**
  - Hydrofluoric acid-based etch
  - Gate air-bridge at mesa edge



L_G = 0.2 μm, L_{DS} = 1.0 μm

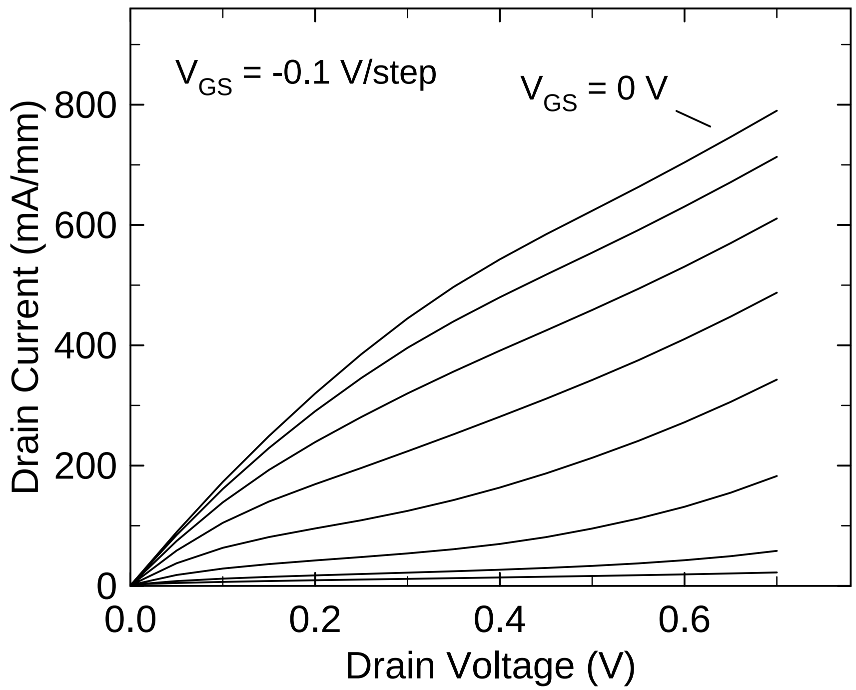
Reduced Impact Ionization in HEMTs with an InAs Subchannel

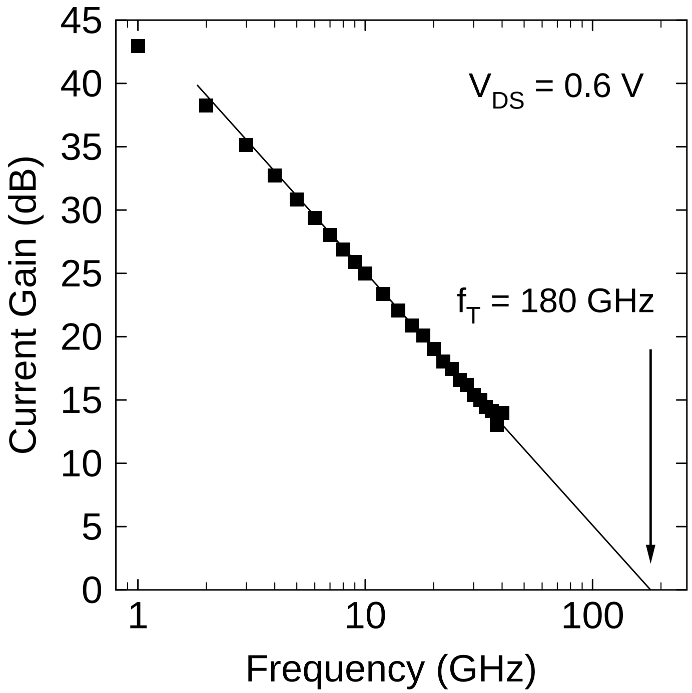




42 Å InAs subchannel reduces impact ionization by transfer of hot electrons to subchannel which has a larger effective bandgap due to quantization.

0.1 μm InAs HEMTs with InAs Subchannel





Microwave Performance at V_{DS} = 0.6 V

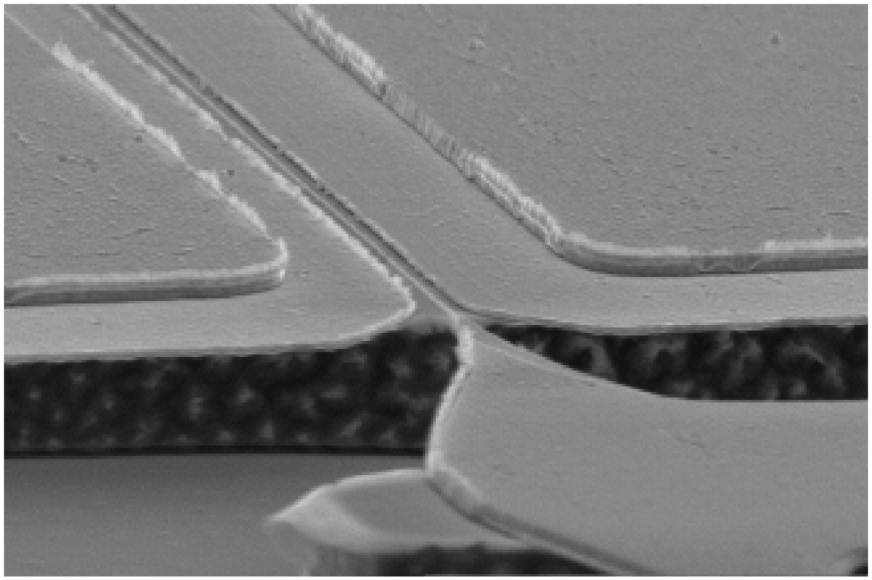
g_m(rf) = 850 mS/mm

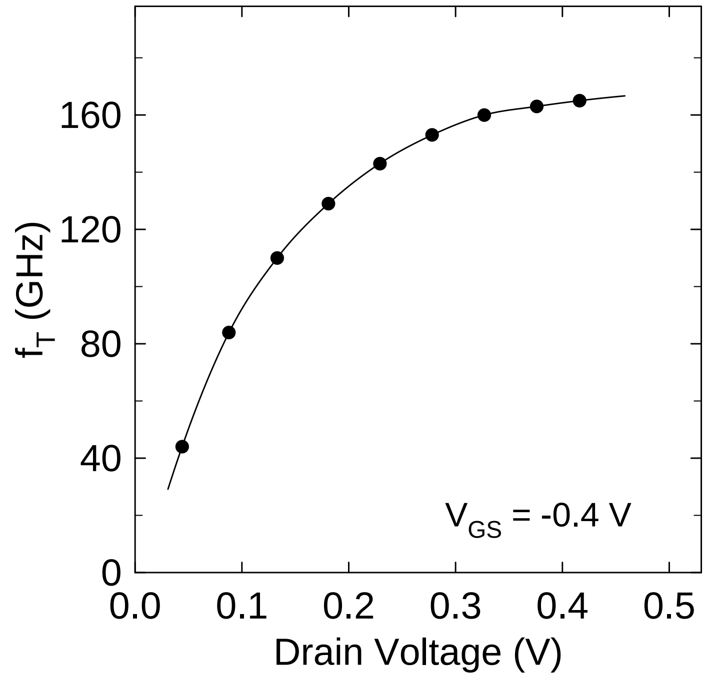
f_T = 180 GHz, f_{max} = 80 GHz

f_T = 250 GHz (after removal of bond pad capacitance)

Ref: *Electron. Lett.*, vol. 34, no. 15, July 1998

60 nm InAs HEMT Characteristics





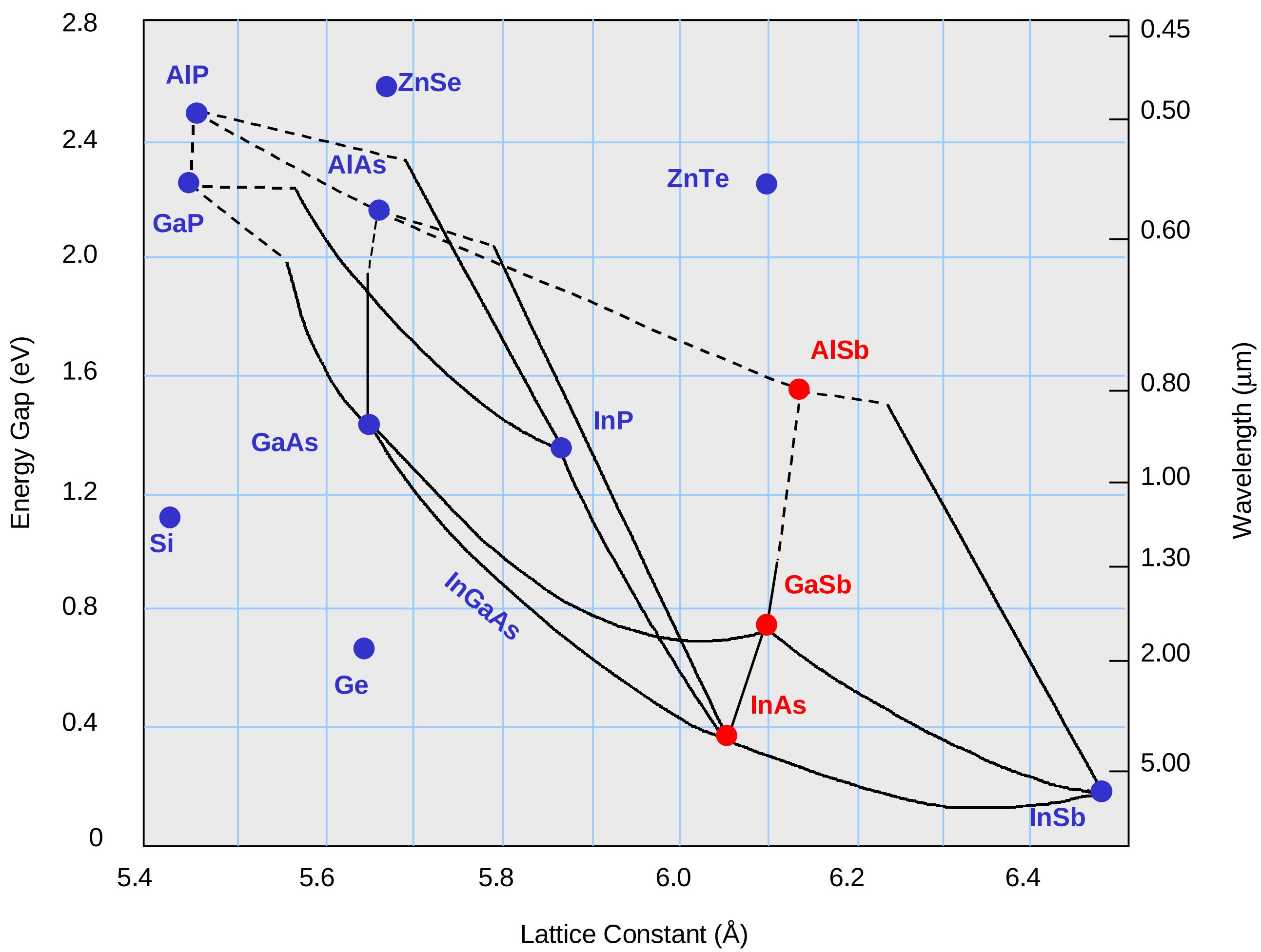
Microwave Performance at V_{DS} = 0.35 V

g_m(rf) = 1 S/mm
f_T = 160 GHz
f_{max} = 80 GHz

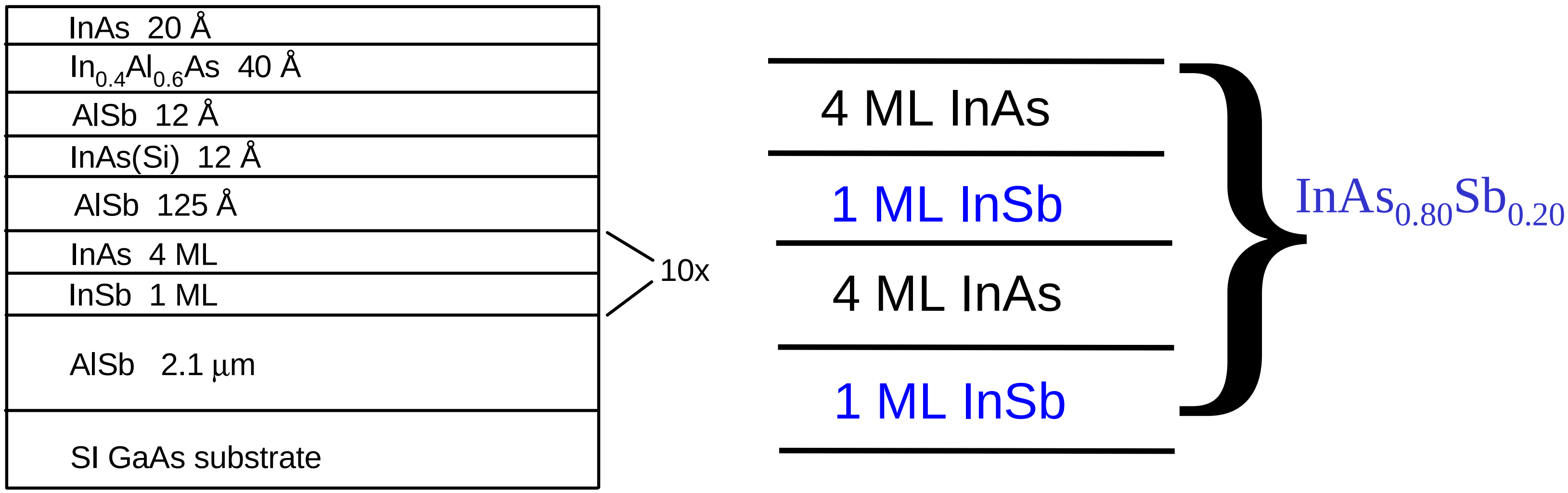
f_T = 90 GHz at 100 mV is highest reported for a FET at this drain bias.

Ref: *J. Vac. Sci. Technol. B*, 17 (3), May 1999

AlSb/InAs/GaSb Material System



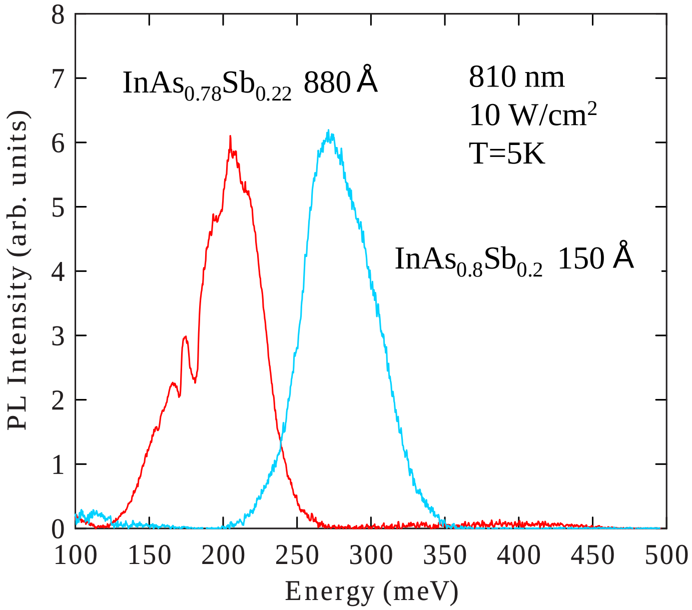
HEMTs with Digital Alloy $InAs_{1-x}Sb_x$ Channel

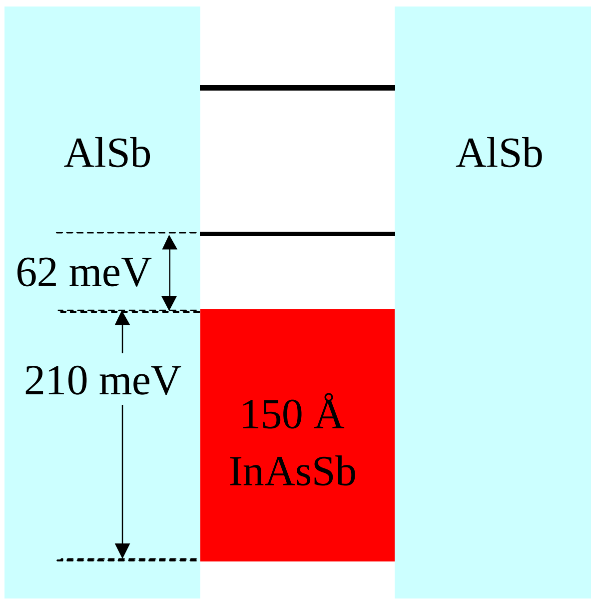


- $InAs_{0.8}Sb_{0.2}$, which is lattice matched to AlSb, was grown as a digital alloy superlattice with 4 ML InAs / 1 ML InSb.
- AlSb/InAsSb has type-I band lineup.
  - more hole confinement
  - lower output conductance

Ref: ***Electron. Lett.*, vol. 35, no. 10, May 1999**

Type-I Band Offset between AlSb and InAsSb

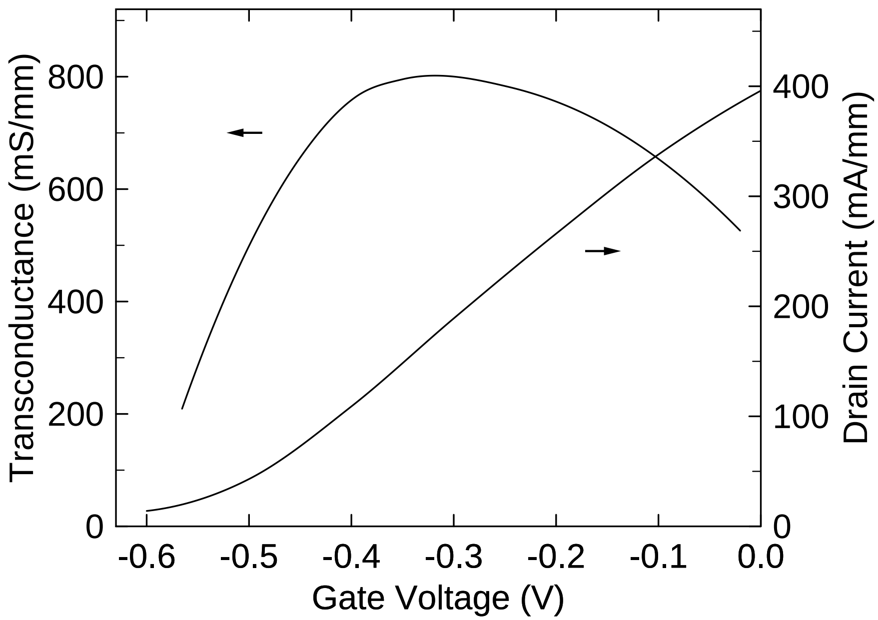


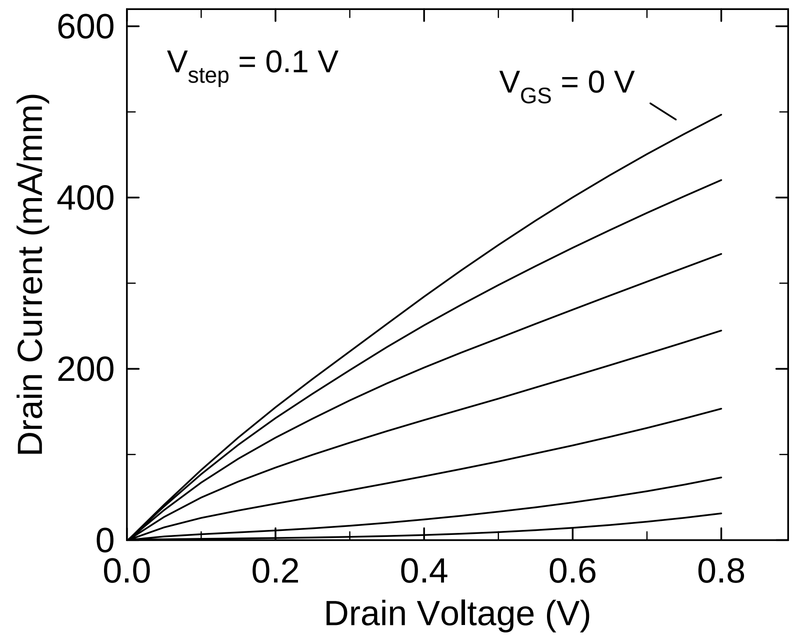


Photoluminescence measurements show the transition from type-II to type-I band alignment occurs around 15% of Sb.

Ref: ***J. Appl. Phys.*****, vol. 87, no. 11, June 2000**

0.1 μm InAsSb HEMT Characteristics



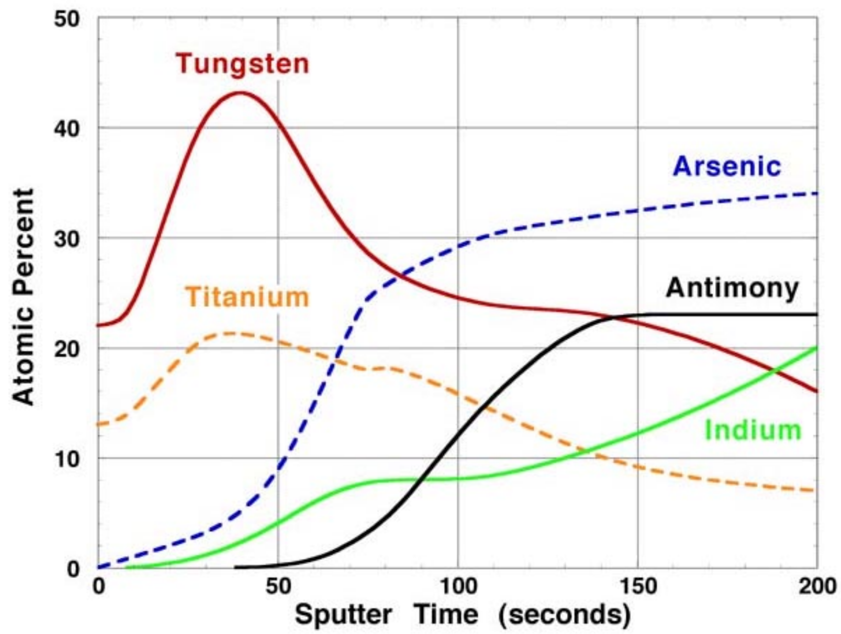


Microwave Performance at V_{DS} = 0.6 V

- f_T = 130 GHz @ V_{DS} = 0.6 V
- $f_{T,\ int.}$ = 180 GHz @ V_{DS} = 0.6 V
- g_m = 700 mS/mm, g_d = 110 mS/mm
- Voltage gain of 6 is highest reported for this material system with this gate length.

TiW/Au Gate Metalization

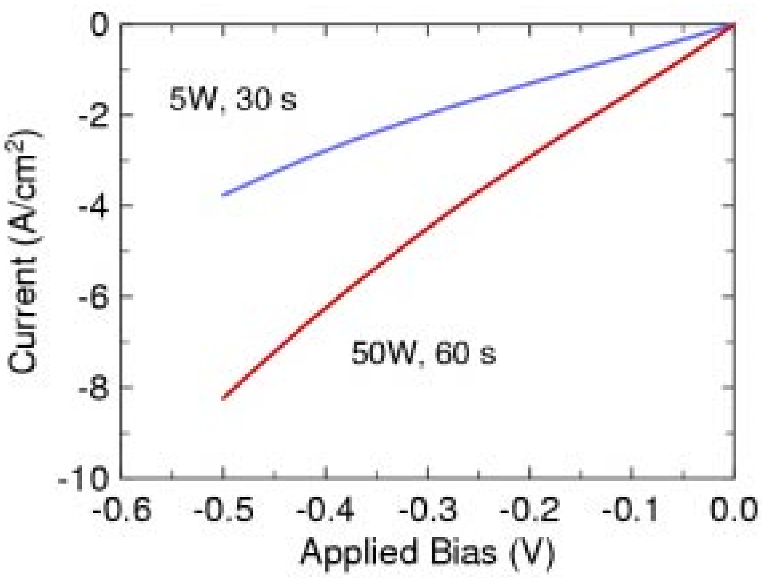
XPS of TiW Layer



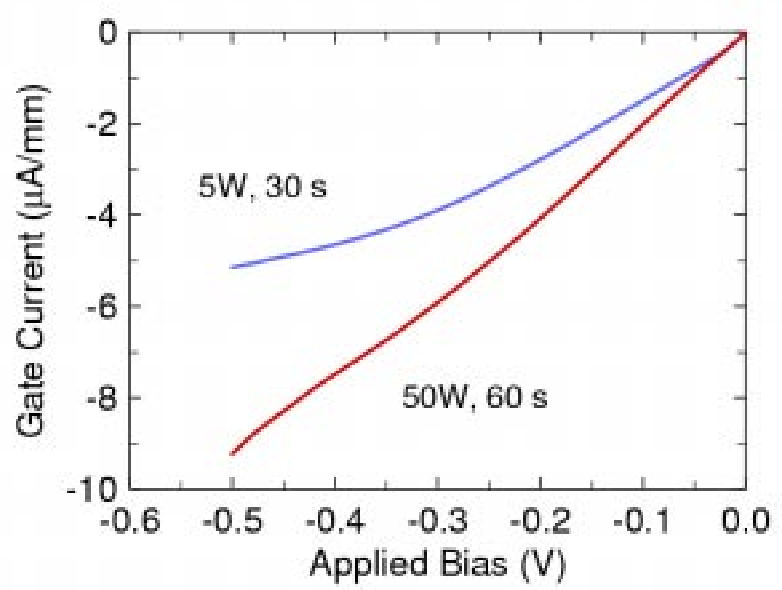
- **TiW/Au gate metalization for increased thermal stability**
  - TiW contacts on GaAs previously shown to be stable to 650°C
  - E-beam evaporated from alloy source (90% W, 10% Ti)
  - XPS indicates deposited layer is 65% W and 35% Ti

Oxygen Plasma Surface Pretreatment

Bond pad before isolation (3200 μm^2)

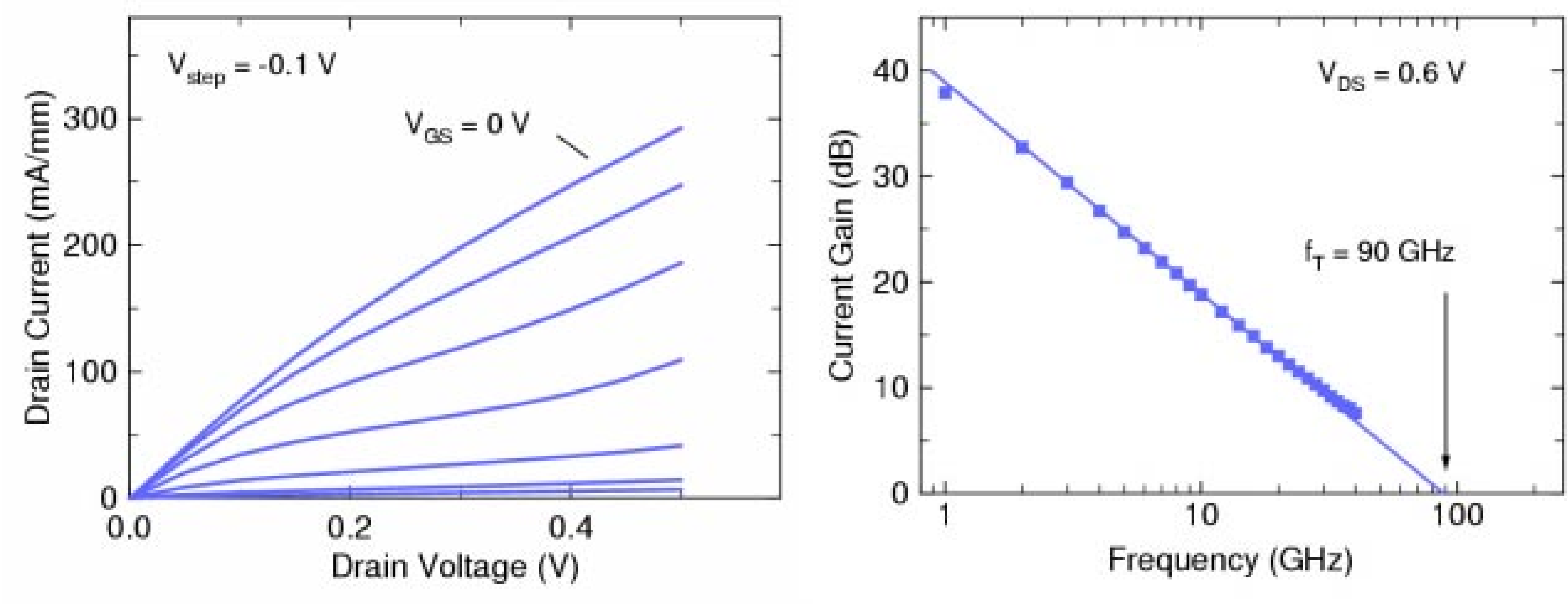


HEMT gate diode after isolation



- **Adjusted oxygen plasma surface pretreatment to reduce damage**
  - Previous treatment: barrel etcher, 50 W for 60 s
  - New treatment: parallel-plate etcher, 5 W for 30 s
  - Diodes with new treatment exhibit 2x lower gate leakage

0.2 μm InAs HEMTs with TiW/Au Gate Metal



HEMT Performance at V_{DS} = 0.6 V

g_m = 750 mS/mm

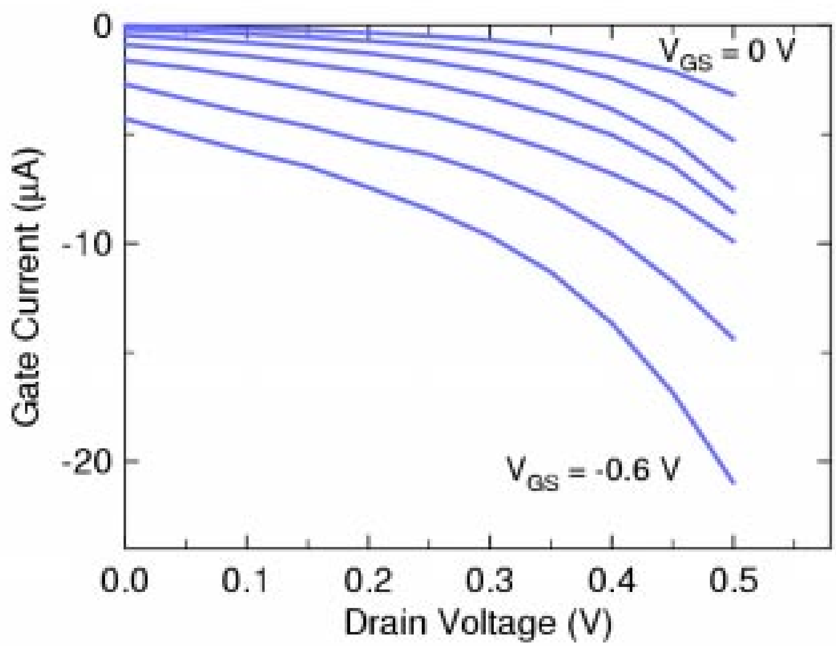
f_T = 90 GHz, f_{max} = 80 GHz

f_T = 120 GHz (after removal of bond pad capacitance)

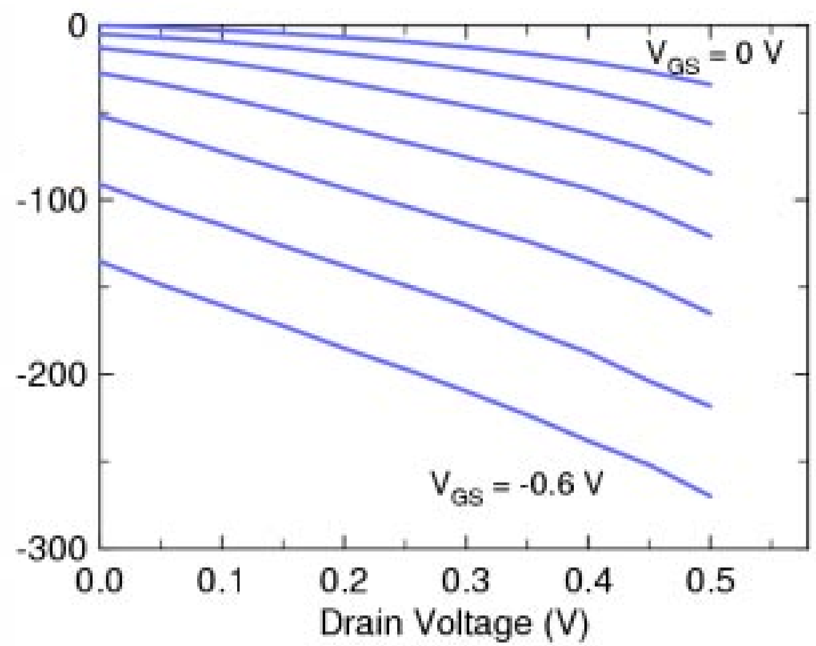
Ref: ***IPRM Proceedings,*** **May 2001**

TiW/Au Gate Leakage Current

TiW/Au gate HEMT



Cr/Au gate HEMT



- TiW/Au gate HEMTs exhibit 10x lower gate leakage current compared to previous Cr/Au gate HEMTs.
- Decrease is believed to be due to reduction in defect-assisted tunneling through the barrier.
- Gate leakage current further reduced by 10x at 77K.

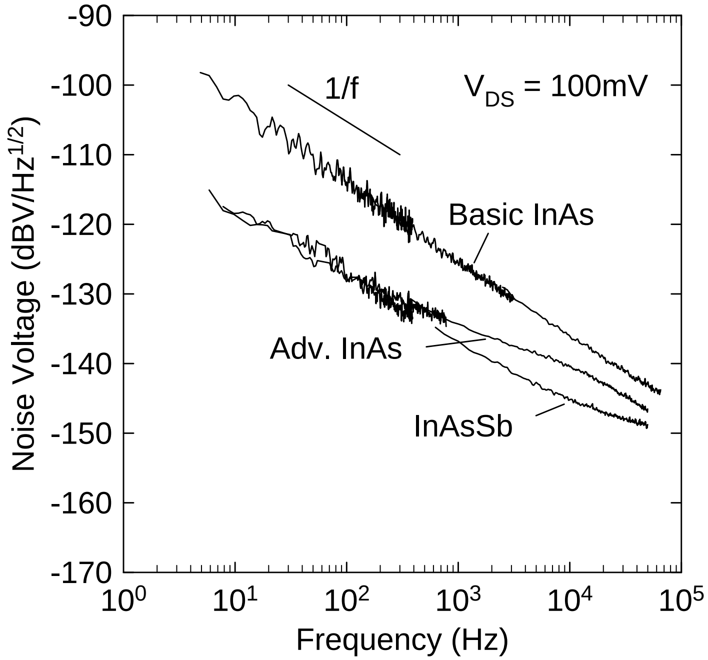
Thermal Stability of TiW/Au HEMT

- Heat treatment:
  - Hot plate located in H_2:N_2 ambient
  - 90°C-210°C in 30°C increments
  - 1 hour duration for each heat treatment

- Only small change observed in reverse current or S-parameters until 210°C treatment.

- Cr/Au gate HEMTs on similar material showed 5-10x increase in reverse leakage current at 150°C.

AlSb/InAs HEMT
Low-Frequency Noise Measurements



Noise Summary

Device	μ	n_S	α_H
Basic	29,000	9.0×10^{11}	6.9×10^{-3}
Advanced	20,000	1.9×10^{12}	1.2×10^{-3}
InAsSb -Channel	13,400	1.4×10^{12}	7.5×10^{-4}

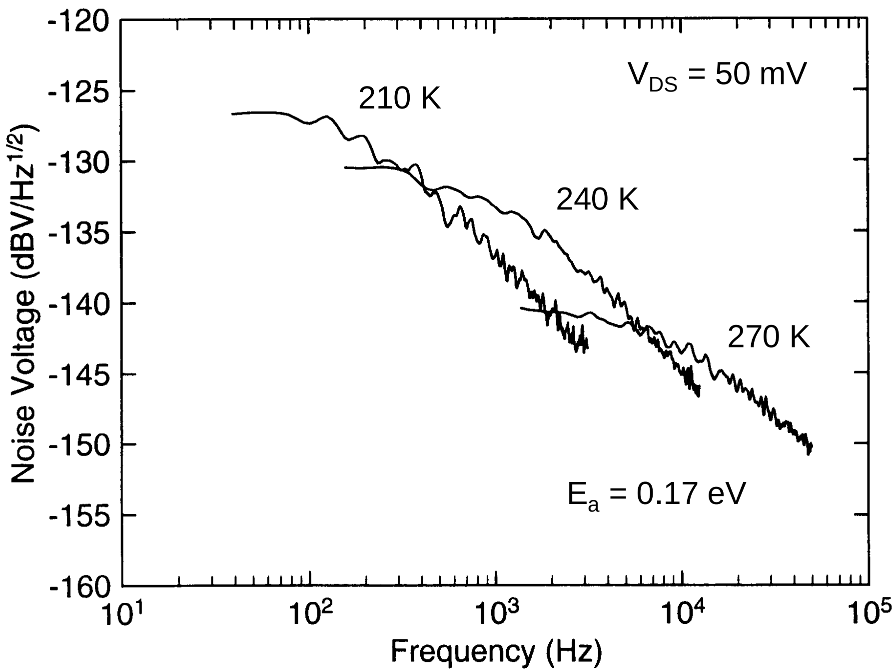
$$S_V = \alpha_H V^2 / N f$$

- First low-frequency noise measurements of Sb-based HEMTs.
- Hooge parameters (α_H) for three types of devices are reasonable for a relatively immature technology.

Ref: ***IPRM Proceedings,*** **May 2000**

Low Temperature 1/f Noise Measurements

InAsSb channel HEMT



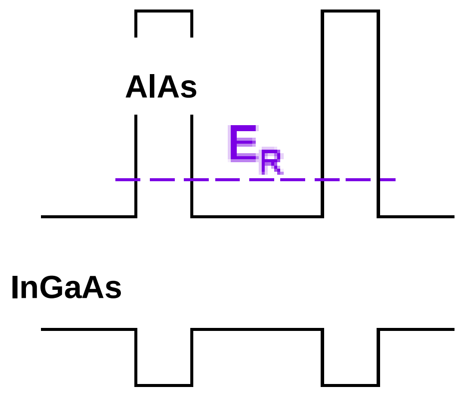
Prominent noise bump moves down with temperature for InGaSb channel HEMT. Activation energy estimated to be 0.17 eV.

Antimonide-Based Resonant Interband Tunneling Diode(RITD)/HEMT Logic Circuits

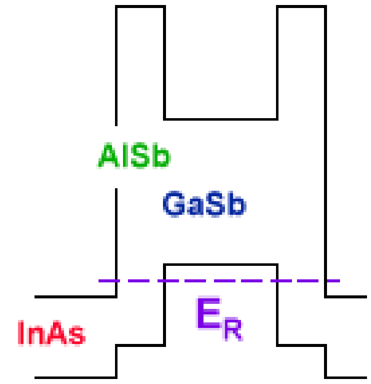
- **Need**
  - Future multifunction radar, EW, and communication systems will require ultra-high-speed and ultra-low-power digital circuits which have reduced chip size and increased density.
- **Potential Solution**
  - RTDs combined with HEMTs result in high functionality, small size, low power consumption, and fast operating speed.
  - Antimonide-based RITD/HEMT logic circuits have potential to set new standards for speed and power consumption.

Advantages of Antimonide-Based RITD/HEMT Logic Circuits

- RTDs combined with HEMTs result in high functionality, small size, low power consumption, and fast operating speed.
- Type II AlSb/InAs/GaSb RITDs are ideal for high-speed, low-power applications.
  - High peak current and low valley current at low drain voltage.
- AlSb/InAs HEMTs perform well at low drain voltage and have potential for lowest power-delay product for any semiconductor.
  - High f_T, f_{max} at low drain voltage
  - Large current drive



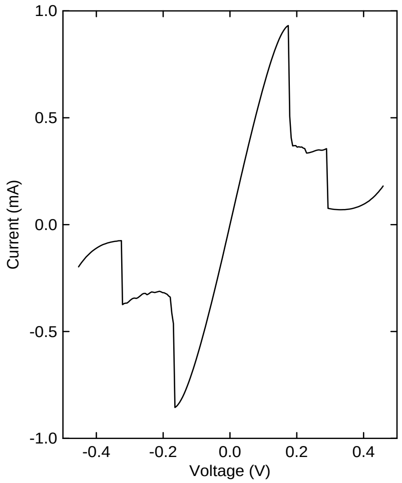
Type I RTD (InP-based)



Type II RITD (Sb-based)

Sb-Based RITD/HEMT Logic Circuits

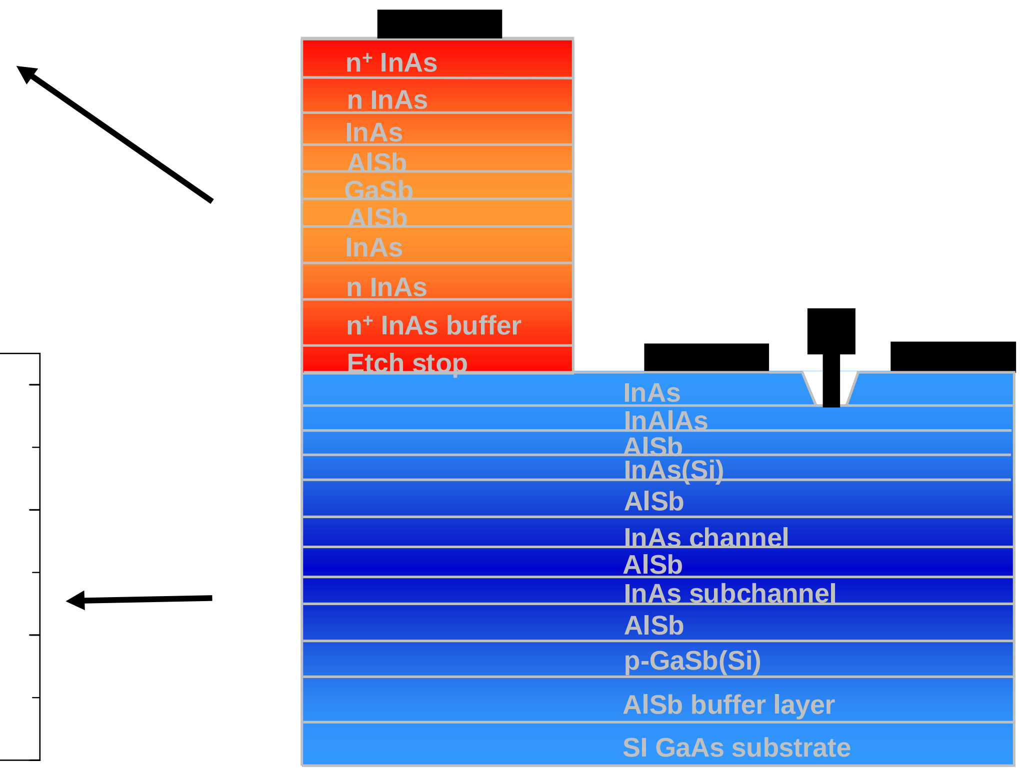
RITD



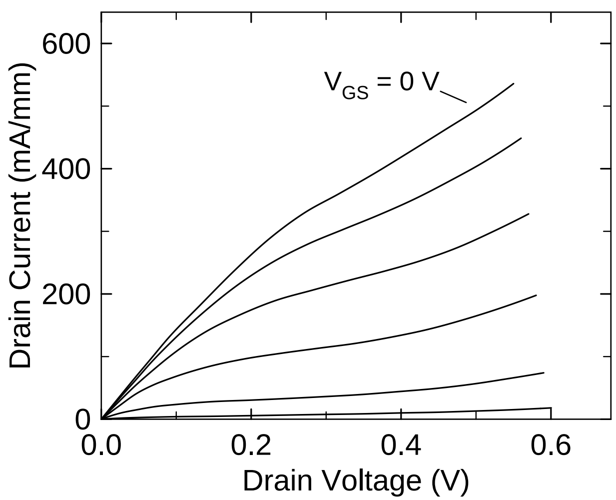
Peak current density: 1.4x10^4 A/cm2

Peak voltage: 0.12 V

Peak-to-valley ratio: 11



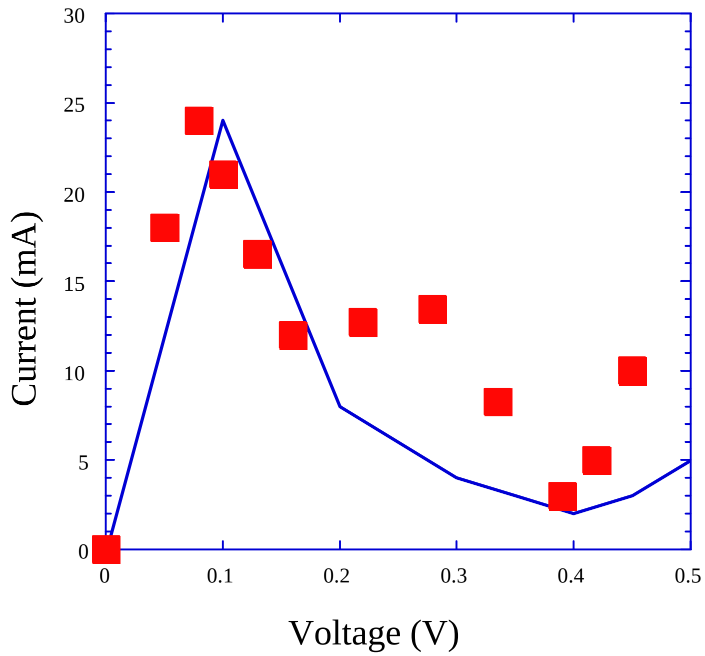
0.1 µm HEMT

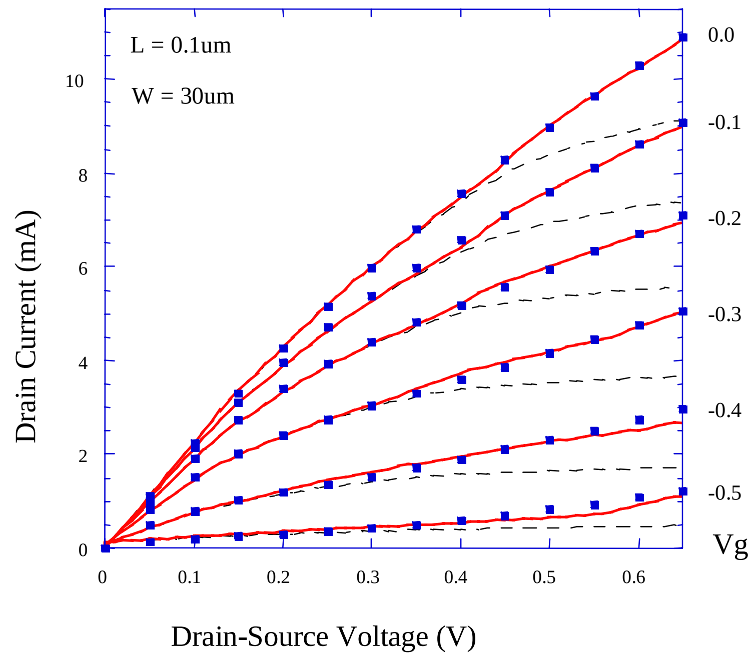


Ref: ***J. Vac. Sci. Technol. B*****, 18 (3), May/June 2000**

Sb-Based RITD/HEMT Simulation

Large-signal model: dc model combined with bias-dependent small-signal equivalent circuit.





Gm: Piecewise linear dc model

Cm: $\dfrac{\varepsilon A}{d + \sqrt{2\varepsilon V/qN}}$ or 4 fF/um^2

Experimental data from R. Magno (NRL)

Ref: *IPRM Proceedings,* May 2000

Phenomenological dc model:

multiplication

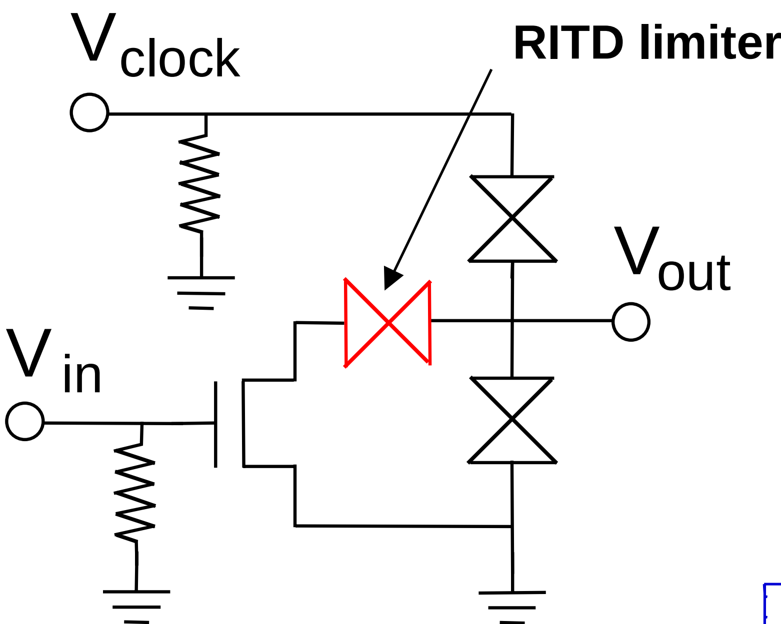
trapping

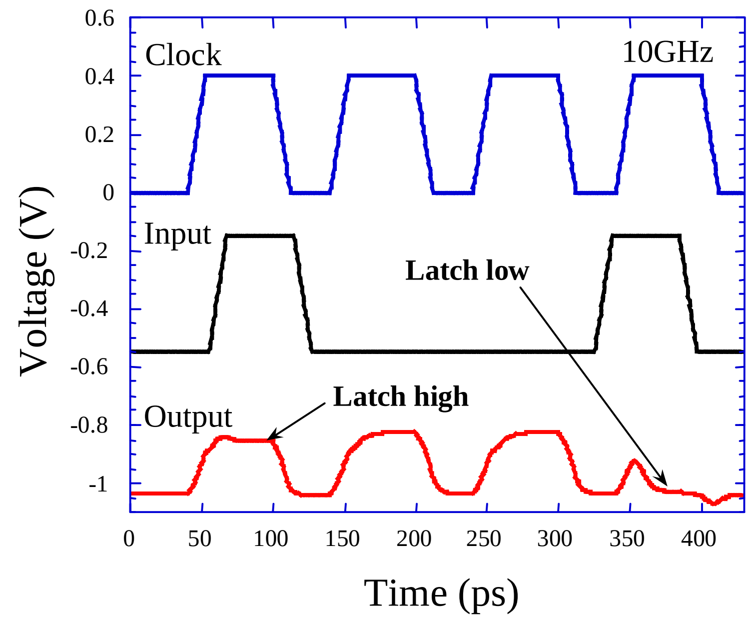
$$I_d = I_o + I_d M + \frac{T I_d M}{1 + \varepsilon I_d M} \cong \frac{I_o}{1 - MT} \equiv I_o(1 + \eta)$$

$M << 1, \quad \varepsilon I_d M << 1$

Sb-based MOBILE Circuit

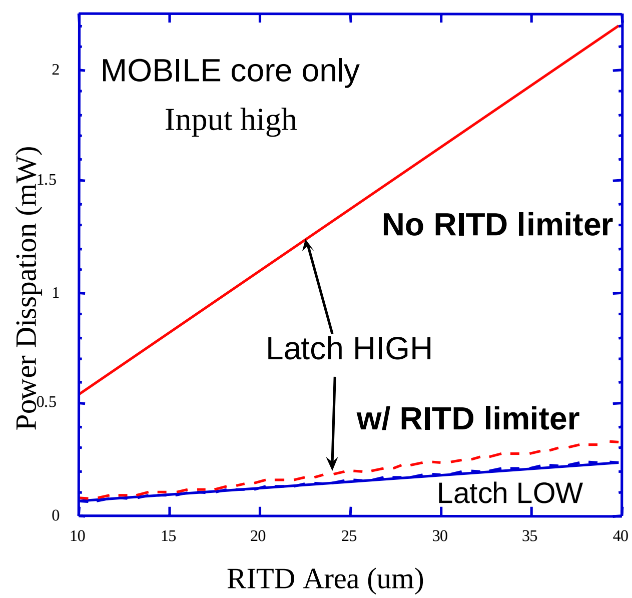
MOBILE-based flip-flop





SPICE simulations

D-flip-flop



Static Power

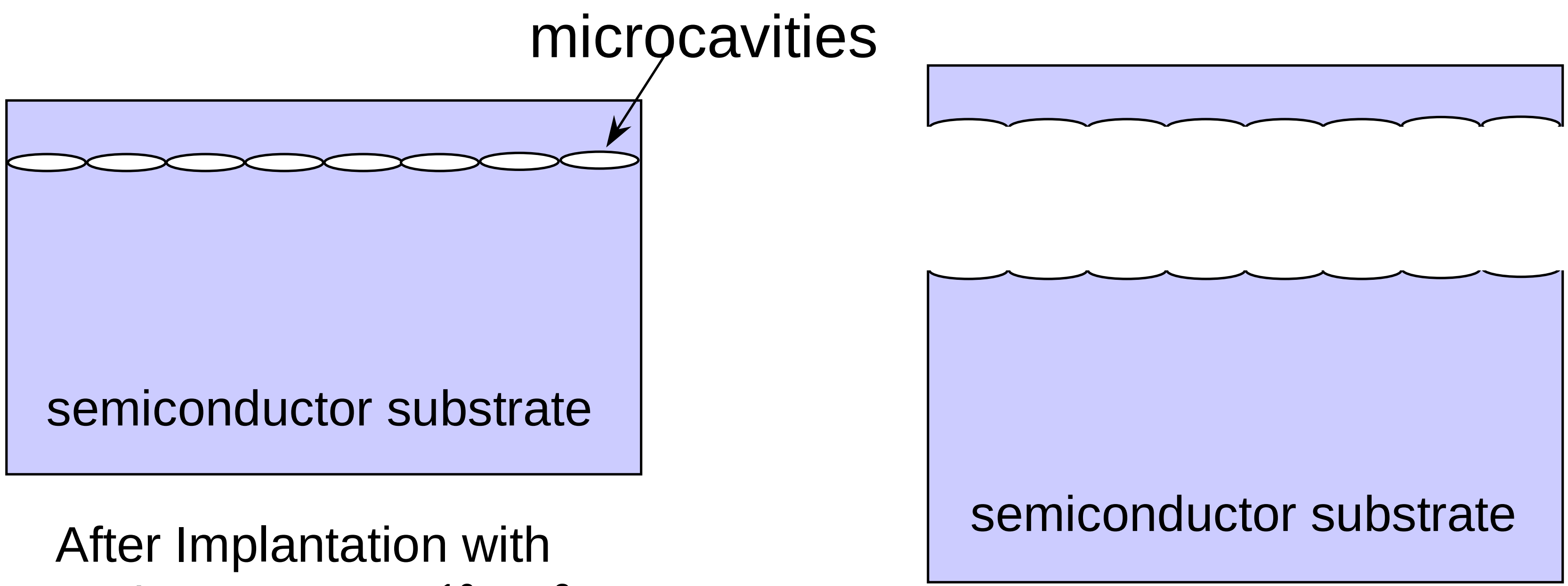
- Addition of RITD current limiter significantly reduces power dissipation. (Pacha et al., *IEEE Trans. VLSI Syst.*, 8 (5), 2000)
- SPICE simulation of HEMT/RITD circuit predicts 5-10X lower power dissipation than comparable InP-based circuit.

Gate Leakage Current Reduction using "Smart-Cut" Layer Transfer Technology

- **Objective:**
  - Fabricate and characterize Sb-based circuits on hybrid substrates to lower dislocation density.
- **Plans:**
  - Develop hydrogen ion-implant layer splitting process to transfer ultra-thin GaSb or InAs layers to an insulating substrate.
  - Grow high-quality HEMT layers which are lattice-matched to the ultra-thin transferred material.

“Smart-Cut” Wafer Splitting Technology

Hydrogen gas expands when heated and splits semiconductor

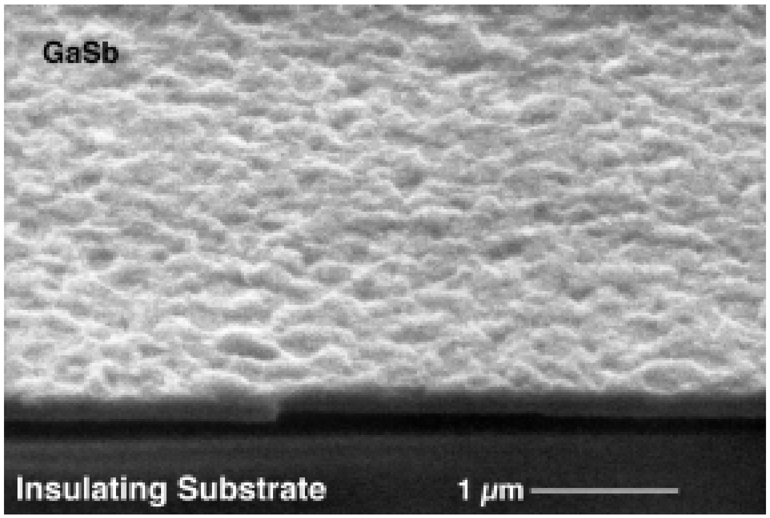


After Implantation with Hydrogen, $>5\times10^{16}cm^{-2}$

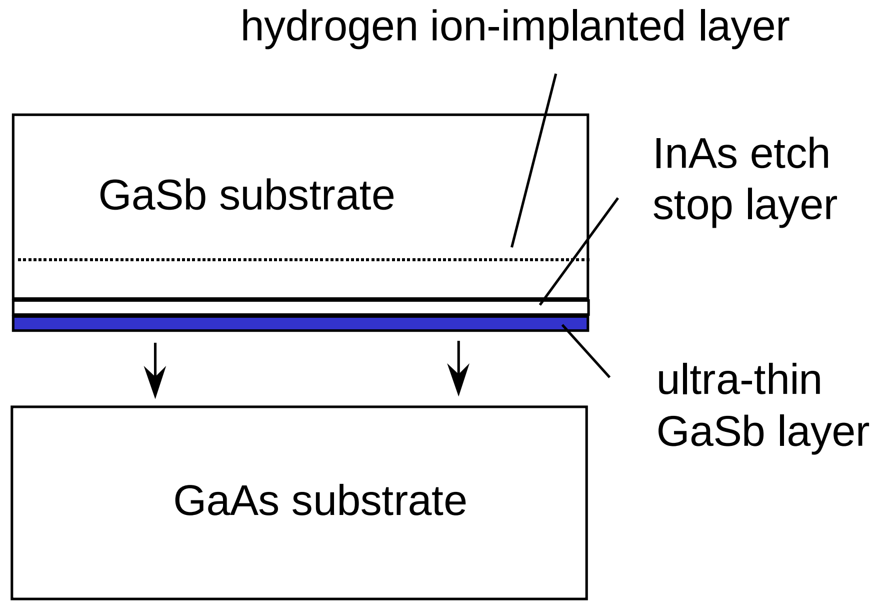
After Anneal

Demonstrated to date for single-crystal Si, GaAs, SiC, Ge, GaN

“Smart-Cut” and Wafer Bonding of GaSb



SEM image of GaSb transferred to insulating substrate.



“Ultra-Cut” Process

First demonstration of wafer bonding and hydrogen ion-implant layer splitting to form ultra-thin GaSb on an insulating substrate.

Ref: *Electron. Lett.*, vol. 35, no. 8, April 1999

Summary

- **Demonstrated 0.1 μm InAsSb-channel HEMTs.**
  - AlSb/InAsSb has type-I band lineup which enables more hole confinement.
  - Voltage gain of 6 is highest reported for this material system with this gate length.
- **Demonstrated 0.2 μm InAs HEMTs with TiW/Au gate metalization.**
  - 10x reduction in gate leakage current at low drain voltage using TiW/Au gate and adjusted oxygen plasma surface pretreatment.
  - HEMTs were thermally stable to 180°C when heat treated in a H_2/N_2 ambient.
- **Performed low-frequency noise measurements of Sb-based HEMTs.**
  - Hooge parameters (α_H) of 10^{-2} to 10^{-3} for three types of devices are reasonable for a relatively immature technology.
- **Demonstrated Sb-based RITD/HEMT integration.**
  - HEMT and RTD performance is comparable to that obtained on discrete devices.
  - Initial PSPICE simulation of HEMT/RTD MOBILE circuit predicts record 5-10X lower power dissipation than comparable InP-based circuit.
- **Demonstrated wafer bonding and hydrogen ion-implant layer splitting ("Smart Cut") of GaSb.**
  - To be used for the growth of high-quality HEMT layers which are lattice-matched to the ultra-thin transferred GaSb material.